AN ATTEMPT TO FRAME A WORKING HYPOTHESIS OF THE CAUSE OF GLACIAL PERIODS ON AN ATMOSPHERIC BASIS

(Continued)

SPECIAL APPLICATION OF THE HYPOTHESIS TO THE KNOWN GLACIAL PERIODS

IT now remains to specifically apply the hypothesis to the recognized glacial periods. At present only those at the close of the Paleozoic and Cenozoic eras are sufficiently determined to require discussion.

The mapping of the Pleistocene glacial deposits is sufficiently complete to show their great features, and reveals a strong development in the northern hemisphere, and at the same time a quite peculiar localization. The analysis of the deposits has progressed far enough to show that the glacial period was marked by pronounced oscillations of both the major and the minor kind. Interglacial epochs of a declared character may be assumed to be fairly demonstrated, while the glacial epochs themselves were attended by rhythmical stages of progress, as most pointedly brought out by recent detailed field work in the Mississippi and St. Lawrence valleys, notably that of Mr. Leverett and of Mr. Taylor. These rhythmical features are made the subject of a special discussion by Mr. Taylor in a paper entitled "Moraines of Recession and their Significance in Glacial Theory."[1]

To be really applicable to Pleistocene glaciation a working hypothesis must therefore not only postulate agencies capable of producing a glaciation covering the American plains down to

[1] JOUR. GEOL., Vol. V., No. 5, 1897, pp. 421–465. See also "The Great Ice-Dams of Lakes Maumee, Whittlesey, and Warren," American Geologist, Vol. XXIV, No. 1, July 1899, pp. 6–38, and the review of this paper by MR. GILBERT in the last number of the JOUR. GEOL.

37° north latitude, and mantling also the plains of middle Europe and high altitudes quite generally, but it must assign agencies for the oscillations which attended it.

General cause.—The atmospheric hypothesis finds a general cause for the Pleistocene glaciation in that notable extension and elevation of the land which reached a climax near the close of the Pliocene period. It is not, however, through its direct topographic influence that this was accomplished, though this may have been incidentally tributary, but through its effects on the constitution of the atmosphere. The recently named Ozarkian or Sierrian period embraces the specially effective stage of this great land area, and it is with much pleasure that I support the emphasis laid upon the significance of this period by Professor Le Conte in his paper in the last number of the JOURNAL,[1] though I interpret that significance in different terms. The wide extent and high elevation of the land at that time are so strongly set forth by Dr. Le Conte as to leave no need for additional emphasis here.

A rude estimate of the land area in Middle Tertiary times, when the climate was mild far to the north, gives about 44 million square miles. A similar estimate for the Ozarkian or Sierrian period gives about 65 million square miles, while the received estimate of present land is about 54 million square miles. Taking the Middle Tertiary area as a basis of comparison, the land was increased in the Ozarkian period about 47 per cent., and afterwards fell off to the present area, which is 23 per cent. greater than that of the mid-Tertiary. It is probably conservative to estimate that the average elevation of the Ozarkian land was at least two or three times, perhaps three or four times, as great as that of the mid-Tertiary. Combined in the light of the suggestions previously made regarding elevation, these indicate a very great change in the effective contact of the atmosphere with the earth. If we measure the actual contact by the surfaces of the grains, pores, fissures, and minute crevices with which the air and the atmospheric waters come in contact

[1] Pp. 525–544.

—and this is the true contact area—the increase will appear impressive.

As in other cases, there was here also a self-accelerating action. As land was elevated, its underground water level was at first carried up measurably with it and lay near the surface. Trench-cutting accompanied it, to be sure, but at a slower rate. As the declivity increased the cutting and transportive power of the drainage increased, and as the dissection of the land proceeded, the water level was lowered and the effective zone of atmospheric contact augmented. The very process of degradation, up to a certain stage, increased the facilities for the chemical action of the atmosphere. In general it may be observed that degradation reacts upon itself favorably for a time. The cutting of certain of the western plains into "bad lands" and the gullying of the cultivated fields in certain parts of the southern states are striking examples of current self-accelerating processes of the more mechanical sort.

Concurrent with this increase of the atmospheric contact-area on land there was a reduction of sea surface, the habitat of lime-secreting life, and, *nota bene*, an almost complete obliteration of the epicontinental seas and sea-shelves which were the parts of the sea bottom that were by far the most prolific in carbonic-acid-freeing marine life. Shallow-water marine life must have been very generally driven down on the abysmal slopes and on to such limited deeper shelves as may have been brought within reach by the lowering of the seas. The consequent lessening in the rate of freeing of carbon dioxide is assumed to have been great, and this coöperated with the accelerated consumption on the land to hasten the depletion of the atmosphere.

Besides this, when any appreciable reduction of temperature followed these coöperating agencies, it tended of itself to check the lime-secreting life of the ocean, and at the same time to give the oceanic waters greater absorptive power and less dissociative activity, thus calling into operation a group of secondary agencies which intensified the effects of the primary agencies.

Now the task assigned this remarkable combination of agencies is not a formidable one. If we take the largest of the current estimates of the present atmospheric content of carbon dioxide, viz. .06 per cent. by weight (comparable to .04 per cent. by volume), the mid-Tertiary atmosphere should have contained .15 per cent. to .18 per cent. of carbon dioxide, and that of the glacial period .03 per cent., following Dr. Arrhenius' estimates. That is to say, for the reduction of the carbon dioxide of the Tertiary atmosphere from the assigned .15 per cent. or .18 per cent. to the assigned .03 per cent. of the glacial period, we have an estimated increase of land area of 47 per cent., and an increase of elevation of 100 per cent. or 200 per cent., and perhaps more. To produce the present amelioration we have a falling off of about one half in each of these items.

Numerical data, which will be given later, indicate that something like $\frac{1}{2000}$ of the carbonic acid of the air is now taken out annually. If the same amount is returned, the constitutional status is preserved. But if the foregoing agencies that coöperated in late Pliocene and early Pleistocene times to disturb the balance between removal and return were effective to no more than 10 per cent. of the total rate, it would have been capable of reducing the assigned mid-Tertiary content of .18 per cent. carbonic acid to the assigned glacial content of .03 per cent. in 50,000 years. It is not, of course, supposed that the rate would be constant as the state of enrichment changed, and note of this will be taken later, but the computation serves to show how effective a disturbance in the relative rates of supply and removal becomes when such action bears so high a ratio to the total mass of carbon dioxide in the air. It may also serve to show that the hypothesis is assigning agencies whose supposable quantitative competency is abundantly adequate to the results imputed to them.

ASSIGNED CAUSES OF GLACIAL OSCILLATION

It has been already noted repeatedly that the assigned causes of glaciation are self-accelerating in certain significant

phases. The salient effect of this, reasoning on general principles, must be to push results to an extreme from which reaction is inevitable. Let us consider this in detail. It is thought that there were three dominant agencies concerned in this, modified by several subsidiary ones.

1. A necessary consequence of the accelerated rate of transmission of carbon dioxide to the sea, combined with a slackened rate of release in the sea, was an accumulation of oceanic carbon dioxide. The primary form of this was an increase of the carbonates.

2. The cooling of the sea waters which attended the process reduced the dissociation, and hence the carbonates were more nearly full bicarbonates than before. *There were, therefore, not only more carbonates, measured by the bases, but they carried more carbon dioxide in proportion to the bases.*

3. With the growth of the snow-fields attendant on the progress of glaciation, there was an increase of reflection of the sun's radiation and a reduction of its absorption. Computation shows that the albedo is an important factor.

Subsidiary to these there were the following:

4. There was an increase in the absorption of carbonic acid in the ocean, resulting from the lowering of the temperature. This, however, was offset by the declining partial pressure of the carbon dioxide in the air, and, as the two seem to be of the same order of magnitude, they may be set aside for the present.

5. With increasing cold there was a less rapid decay of organic matter and a less complete release of carbon dioxide. Over against this, however, there was a reduction in the amount of carbon locked up in living organic matter. It is difficult to form a trustworthy estimate of either, but it may be provisionally assumed that they belong to the same order of magnitude and may be set aside together. At any rate, any residual difference would not apparently be a notable factor.

6. The majority of chemical authorities state that the solubility of calcium carbonate in water saturated with carbonic acid increases with a lowering of temperature through ordinary

ranges. Unfortunately there is not complete unanimity on this point. But, if this be true, as the temperature fell the solvent action of the carbonic acid of the land waters upon the limestone was increased. Over against this was a probable reduction of the action of organic acids. Probably the decomposition of the silicates went on at a lower rate, but, as it was much less than one fifth of the whole action, its reduced rate is not very material here.

As the carbonic acid of the air was diminished, its action on the land surface declined—though not at a proportional rate—but long before it could offset the enlargement of the contact area aided by the sea action, glaciation would be far advanced, if the previous estimates hold good.

Setting aside, as being measurably balanced, or as being of minor or uncertain value, all but the first three items, which are clearly factors of great potency, we find at first a strong disposition toward the acceleration of the depleting process.

But this, although a pronounced influence in the early stages of refrigeration, could not continue indefinitely, for the process involved the conditions of its own arrest.

The arrest of the depletion and the inauguration of the reaction.—With the development of glaciation, the agencies that tended to counteract atmospheric depletion received a powerful ally in the ice-sheet itself. The spread of the ice over the surface prevented further effective weathering of the area so covered and correspondingly arrested atmospheric depletion. The total area covered by glaciation at its maximum was probably not far from 8 million square miles, or nearly 15 per cent. of the land surface.

Besides this, the area outside of that actually covered by the ice-sheets was probably affected by prolonged freezing during the winter stages, and was perhaps to some extent permanently frozen beneath the surface, and this arrested solvent and chemical activity. If the modest figure of 5 per cent. be assigned for this supplementary effect, 20 per cent. of the functional area would be withdrawn from action. Whether this numerical estimate be correct or not, it may be assumed that if a given amount

of withdrawal, combined with associated agencies, were not sufficient to arrest the progress of glaciation, the glaciation would have continued to extend itself until the point of balance was reached. It is, perhaps, not too much to assume that the extension of glaciation and its concurrent agencies mark in themselves the measure of preponderance of the depleting agencies at the stage when glaciation began. That is to say, after the depleting agencies had brought the air's carbonic content down to the point at which the glacial centers were inaugurated, these agencies were still preponderant over the repleting agencies to some such extent as 20 per cent., more or less.

While it does not seem necessary to our general purposes to consider the associated agencies of arrest, if these views be correct, they possess an interest of their own, and may be mentioned briefly.

With little doubt the lowering of the temperature lessened the rate of decomposition of the silicates, though frost action aided in disaggregating them mechanically and in thus increasing the atmospheric contact. On the other hand, while the authorities are not altogether agreed, the weight of the latest opinion supports the view that the limestones would be dissolved by cold water saturated with carbon dioxide faster than by warm water, other things being equal. The cold waters would quite certainly contain more absorbed carbon dioxide than warm ones. Probably other things were not equal, for the vegetable action and the organic acids probably lent less and less aid as the temperature fell. It is not clear what the balance of these influences combined would be. Whichever way it leaned, it does not seem to have been of decisive moment.

As previously remarked, the progressive removal of carbon dioxide from the air reduced the amount of its action, but not proportionately. While this lessened the depleting action it does not seem to have reached decisive moment, at least not until a late stage in the process of depletion.

Meanwhile, in the ocean, conditions favoring reaction were

gathering force as the result of the processes in action there. The ocean was accumulating carbonates and augmenting their degree of bicarbonation with the increase of cold. Now it is obvious that if the loading of the ocean with carbonates were to proceed to the point of saturation, inorganic processes of precipitation and dissociation would come into play to an extent that must necessarily balance all further accessions of material. It does not appear, however, that there is enough, or even nearly enough, carbon dioxide in the air to bring about a condition of full saturation of the ocean with bicarbonates, even if it were all to take that form, and were to be conveyed completely to the sea. But the movement toward saturation should increase in some degree, probably small, the efficiency of inorganic agencies tending toward precipitation, although it could become notably effective only after prolonged accumulation.

The concentration of carbonates in the ocean was somewhat aided by the removal of water required to form the great ice-sheets. On a rather large estimate of the mass of the ice-sheets, this extraction might possibly reach 5 per cent. of the volume of the ocean.

There would probably be a progressive evolution of lime-secreting life adapted to the cooled waters, and this would increase the rate of carbonic release and contribute to a reversal of action.

None of these subsidiary agencies, nor all combined, seem to have been controlling factors.

It is notable that some of these subsidiary agencies, on both sides, are final in themselves and quite without retroactive possibilities. When once their work was done there was no resilience. It was quite otherwise with the ice mantling and the ocean loading. Far from being final, these contained in themselves the potentialities of reaction and gave vigor to the reaction when it took place.

Agencies that precipitated reaction.—When once the reactive agencies had reversed the relative rates of enrichment and

depletion and there began to be an increase of carbon dioxide in the air, the following influences would coöperate to hasten and intensify the reactive movement.

1. The dissociation of the second equivalent of carbonic acid associated with the carbonates of the ocean would be increased, and as the temperature rose from the diffusion of the freed carbon dioxide into the air this would be still further augmented by its own reactive effects. This is one of those interesting agencies whose effects at once become causes of further like effects.

2. The increased warmth would call forth more lime-secreting life in the ocean, and thus also hasten the freeing of carbon dioxide, and this again would react favorably on itself.

3. The increase of water from melting ice would somewhat extend the shallow-water zone and favor lime-secreting life. If the land were depressed by the load of ice, as some suppose, this would increase the sea area and favor lime-secreting life. With this may be associated the falling of the water level in the high latitudes (to which it had been drawn by the gravitation of the accumulated ice mass) and a corresponding rise of the water level in lower latitudes. Since the lower-latitude life is more abundant than the high-latitude life, and more effective in extracting lime, the shift would involve a gain in lime-secreting potency.

4. The increased decay of organic matter attendant on the warmer temperature would develop carbon dioxide; but over and against this must be set the increased carbon locked up in the augmented living matter. These, as before, are set aside, as perhaps mutually offsetting each other.

5. The increase of temperature arising from the preceding causes would increase the water vapor in the air and thereby add to the thermal capacity of the atmosphere, and this would react favorably upon itself and upon the other agencies favored by high temperature.

Thus the reaction once started would be self-augmenting,

until the fundamental conditions were changed or the reaction was checked by its own ulterior consequences. The sequences may be easily followed. The carbonates of the sea, which had been augmented during the epoch of glaciation were now diminished and limestone was more actively deposited. The ocean, previously fattened in carbonates now became lean. So also the carbonates themselves, that before were quite plump bicarbonates, now became degraded to a mixture of normal and acid carbonates. In short, the ocean holds less free and feebly-combined carbon dioxide and the air holds relatively more. As the ocean is now estimated to contain from eighteen to twenty-five equivalents of atmospheric carbonic acid in the free and feebly-combined states, a moderate fluctuation in its content would cover the full range of atmospheric variation required to produce the climates under discussion, according to Arrhenius. On the supposition that the glacial epoch was produced by a reduction of the carbonic content of the atmosphere to one half the present amount. it would only be necessary for the ocean to release 2 or 3 per cent. of its releasable carbon dioxide to restore the atmosphere to the present condition. If the ocean gave up 4 or 5 per cent. of its releaseable carbon dioxide the climate would be notably milder and more equable than the present. Assuming the correctness of Dr. Arrhenius' conclusions, it would seem from these considerations that there is nothing forced or violent in the supposition that an effective interglacial epoch might be brought about by the reactive agencies indicated.

Recrudescence of glaciation.—If the land area of the globe as a whole remained large and high notwithstanding such local depressions as have been attributed to the weight of the ice and the effects of low temperature; or, more precisely, if the atmospheric contact area remained large, the conditions for a renewal of glaciation would again prevail because the renewal of warm temperature, the enrichment of the atmosphere, and the depletion of the ocean would restore the original action. So soon as the ice had retreated from the land, the weathering of the

uncovered area would be renewed. This, of course, would begin so soon as the retreat began, and increase in a corresponding measure; but it is a slow process, while the reactions of the ocean are relatively rapid—indeed they should keep close pace with the rise of temperature which they induce. There should be no appreciable lag. After the retreat of the ice a new surficial factor would come into play, the sheet of drift spread over the surface. In so far as this consisted of undecomposable matter blanketing decomposable matter, it would interfere with the progress of decomposition, but in so far as it consisted of limestones and silicates ground to a flour and exposed to the atmosphere, it would facilitate chemical action and expedite a second depletion of the atmosphere and through it a second term of glaciation. Aside from the effects of this mantle of drift and such changes of topography as might have occurred, the conditions for the renewal of glaciation would be, so far as I see, as effective as they were at the outset. Assuming that they were equal to the preceding, a second glaciation equal to the first is to be postulated, and a corresponding reaction at length, as in the previous case, due to like agencies. Thus a series of glaciations and deglaciations should follow each other until the general causes lying back of glaciation had disappeared.

In so far as the land, on the whole, settled back toward sea level or was worn away, or, by any other agency, lost its degree of effective exposure to the atmospheric action, in so far the conditions of glaciation would disappear. Pursuing the normal history which follows a period of great land elevation, it is to be presumed that there would be a gradual reduction of the land surface and land elevation, and that hence the conditions productive of glaciation would gradually pass away. On such an assumption it is presumed that the recurrent glacial advances and retreats would become more and more feeble until the series vanished. Nominally, then, the glacial and interglacial epochs should form a rhythmical series declining from large oscillations at the maximum to lesser and lesser oscillations as the series

disappeared. This seems to correspond with the observed oscillation of glaciation in both Europe and America.[1]

INTERCURRENT AGENCIES

Without question the normal series of glacial oscillations just postulated would be subject to intercurrent influences which would be liable to disturb, perhaps quite seriously, its regularity and symmetry.

1. Any notable movement in the land which affected the sum total of the atmospheric contact area would disturb the symmetry of the series.

2. Any notable change in the original supply of carbonic acid through volcanic action or other agency would produce obvious modifications. The deformation of the body of the earth out of which the conditions of glaciation are assumed to have sprung would doubtless be favorable to volcanic action, and if this reached a degree of intensity sufficient to add appreciably to the carbon dioxide of the atmosphere, it would radically affect the ongoing of the process. That there was extensive vulcanism nearly or quite concurrent with glacial action has been urged by some geologists; indeed, glaciation has even been attributed to volcanic action.

3. The precession of the equinoxes has been regarded by many thoughtful students of glaciation as an influential agency. If affective, it would superpose a rhythm of its own upon the rhythm postulated by this atmospheric hypothesis. For specific illustration the extensive series of moraines which marked the later stages of the Wisconsin epoch of glaciation are referred by Taylor to precessional influence, while the Wisconsin glaciation itself would, under the atmospheric hypothesis, be referable to atmospheric depletion. The most serious question which here arises is the compatability of the prolonged period implied by Taylor's interpretation with the rate of reaction implied by the

[1] The Classification of European Glacial Deposits, JOUR. GEOL., Vol. III, No. 3, pp. 241–269, JAMES GEIKIE; The Classification of American Glacial Deposits, *ibid.*, pp. 270–277, T. C. CHAMBERLIN; editorial, *ibid.*, Vol. IV, No. 7, October–November 1896, pp. 873–876.

atmospheric hypothesis.[1] This will be more evident as we touch on the time rates.

4. The change in the eccentricity of the earth's orbit which Croll has made the foundation of his beautiful hypothesis of glaciation, if not found competent to produce general glaciation itself, might still be effective in producing climatic changes of less degree, and might superpose important modifications upon the series postulated by the atmospheric hypothesis. It may be remarked in passing, however, that the computed variations of eccentricity of distant periods of the past do not rest on so firm a mathematical basis as is currently supposed.

It is obvious that these and other possible agencies might work concurrently with the atmospheric influences, or antagonistic to them, in either case distorting and masking the normal rhythmical expression which a purely atmospheric series would assume.

DO THE TIME RATES FALL WITHIN WORKABLE LIMITS?

The working capabilities of a glacial hypothesis are somewhat severely conditioned by its time factors. It must not only present a satisfactory correlation between the time of occurrence of glaciation and that of the assigned cause, but the rhythmical action of the cause must be consonant with the rhythmical history of glaciation. That the Pleistocene glaciation followed the Ozarkian or Sierrian stage of elevation at an appreciable distance, I hold to be demonstrated by the relations of the glacial deposits to the eroded topography of that period. On the other hand, there is no evidence of a prolonged interval, geologically speaking. The atmospheric hypothesis demands that the accelerated erosion due to elevation (or rather to the dissection that followed elevation) should have continued long enough to remove about three times the present atmospheric content of carbon dioxide before glaciation could begin, following Arrhenius' computations. This removal could only be accomplished by the *excess* of consumption of carbon dioxide over supply and there is

[1] See GILBERT'S review in last number of this JOURNAL, p. 621.

reason to believe that the rate of supply from the interior was greater than the average on account of crustal disruption and volcanic action. There seems, therefore, little ground to think that the glaciation should have followed closer after the elevation than it seems to have done. It would seem rather that the hypothesis was happy in this time relation at least.

With most geologists, I doubt not, the chief question will be whether the postulated agencies could cause the glacial oscillations, involving the removal and reproduction of the ice, in large part or in whole, as rapidly as the field evidence requires. Present measures of glacial rates and times are quite uncertain but not indefinitely so. Some rude approach to their value may be attained. Recently expressed opinions regarding the time since the last ice retired from the site of Niagara River, and inaugurated the erosion of its gorge, lie between 7000 and 33,000 years, which we may average at 20,000 years. I place no special confidence in this figure, but it is rudely representative of the average order of magnitude of expressed opinion. This represents only a part of the time since the beginning of the deglaciation that removed the Wisconsin ice-sheet. According to Taylor's views it would be only a very small part. I doubt if any careful geomorphic geologist familiar with all the phenomena involved would seriously consider an estimate that made it much more than one half at the most; so that it would apparently not be straining the evidence to take 40,000 years as a rude measure of the time since the beginning of the retreat from the outermost moraine of the Wisconsin stage. However, this may probably be cut in half and halved again without over-straining the possibilities of the hypothesis.

This is the time of retreat. An interglacial epoch involves not only the time of retreat, but the time of interglacial mildness and the time of re-advance. The best specific data now available in America for estimating these elements are undoubtedly those afforded by the excavations about Toronto which have

been so fruitfully cultivated by Hinde, Coleman, and others.[1] (1) The time occupied in the ice retreat is there almost without record. (2) The duration of the mild climate is recorded in thirty-five feet of clays and sands. It is also implied in the time necessary for the migration of the Paw Paw, Osage Orange and other trees from more southerly regions to this rather northern locality, and also for the migration of the clams and other molluscs from the Mississippi waters to this rather distant region. Both of these migrations were probably rather slow processes. (3) The initiation of the returning cold is recorded in 150 feet of fine stratified peaty clays and sands. (4) Following this there was an unknown period occupied in the transition from the conditions of deposition, during which the preceding series had been formed, to the conditions of effective erosion which followed. To suppose that this transition was due to the removal of an ice-dam that had lingered in the lower St. Lawrence seems quite untenable for a long, mild period and a long, cool, but not glacial, period had intervened. It was probably due to the cutting down of the drainage outlet, or to a surface movement, or the two combined, and hence probably occupied an appreciable time. (5) There then followed a period of erosion comparable to that since the last ice invasion. Succeeding this came the re-invasion of the ice-sheet.[2] These data seem to fairly imply that the interglacial epoch represented at Toronto was several times as long as the postglacial epoch.

While nowhere else has so complete a record been found, many estimates of the differences of erosion of the several till sheets in the Mississippi valley, where the formations are well deployed and happily suited to such studies, have been made

[1] GEORGE JENNINGS HINDE: Glacial and Inter-Glacial Stages of Scarborough Heights. Can. Jour. 1878, p. 388 *et seq.*

A. P. COLEMAN: Am. Geol., Vol. XIII., February 1894, pp. 85–95. Ditto. JOUR. GEOL., Vol. III., No. 6, 1895, pp. 622–645.

[2] Canadian Pleistocene Flora and Fauna: Report of the Committee consisting of Sir J. W. Dawson (chairman), Professor D. P. Penhallow, Dr. H. M. Ami, Mr. G. W. Lamplugh and Professor A. P. Coleman (secretary), appointed to further investigate the flora and fauna of the Pleistocene beds in Canada.

by experienced glacialists, and their concurrent judgment is that the least of the notable interglacial intervals was at least two or three times as great as the postglacial interval. It would not be exceeding current judgment, therefore, to assign from 80,000 to 120,000 years as the duration of a typical interglacial epoch.

But in the interest of conservatism let the postglacial interval be taken at 10,000 years and the interglacial at 20,000 or 30,000 years. This seems to me excessively conservative. If the assigned agencies can affect a reënrichment of the atmosphere in carbon dioxide to an amount somewhat exceeding the present content and then again a depletion of one half within 20,000 or 30,000 years, the hypothesis will not be excluded by time limitations.

We have the following pertinent data based in part on Reade's[1] estimates of the present rate of removal of carbonates:

Total mass of the atmosphere - - - - - -	5×10^{15} tons
Mass of atmospheric CO_2 (reckoned by weight at .0006) -	3×10^{12} tons
Total mass of CO_2 taken annually from the atmosphere -	162×10^7 tons
Mass of CO_2 consumed annually in original carbonation (reckoned by area at 20 per cent. of the land) - -	27×10^7 tons
If reduced one half on account of the slower rate of decomposition of crystallines it will be 13.5×10^7 tons, in which case the other half is to be added to the following item, if Reade's estimates are correct.)	
Mass of CO_2 consumed annually in forming bicarbonates -	135×10^7 tons
Time required at this rate to consume total atmospheric CO_2, assuming no return - - - - - - -	1852 years
Time required at this rate, without return, to consume one half atmospheric CO_2 (the reduction requisite for glaciation.) - - - - - - - - -	926 years
Time required to consume half the "free" and "loose" CO_2 of the ocean (estimated at 18 times that of the atmosphere) without return - - - - - -	16,668 years
Time required to consume half the CO_2 of the atmosphere and the ocean combined, without return - -	17,594 years

The last items which involve the reduction of the carbon dioxide in the ocean as well as in the atmosphere are not really

[1] Loc cit. on p. 569.

pertinent to the discussion, if the foregoing doctrine relative to the mode of action of the ocean during a glacial period is correct, for it is there maintained that the ocean does not give up its carbonic acid with increasing depletion of the atmosphere, but, on the contrary, increases its content. They have some interest, however, in connection with it and with other phases of the atmospheric hypothesis which the reader may possibly wish to consider. They also have some pertinency to the discussion of Paleozoic glaciation, to be taken up presently.

We are here concerned especially with the rate at which atmospheric carbonic acid may be consumed to the amount of one half the total content. For convenience, no account has been taken of the return of carbonic acid from the ocean or through organic action. We reach the rather startling result that if there were no return, the decomposing and solvent action on the present contact area would consume one half of the atmospheric carbon dioxide in less than 1000 years. This result, based on Reade's estimate, may be checked by independent computation on a more familiar basis and by different modes of computation. For example, by assuming the average rate of degradation of the land surface to be one foot in 5000 years, and that the carbonates constitute 15 per cent. of the material removed, one half of the carbonic acid of the atmosphere would be consumed in 1248 years, if there were no return; or in 1000 years if the degradation was one foot in 4000 years.

The actual depletion must, of course, depend upon the excess of this rate of removal over the rate of return. I have already endeavored to show that there was a very large fluctuation in the conditions that determined the relative rates of consumption and return, notably that the land of the Ozarkian time was more than 20 per cent. greater in area than the present land, and that its elevation was probably 100 per cent. or 200 per cent. greater at the maximum stage of protrusion. And this was correlated with coöperating conditions in the ocean. Both of these estimates, however, must be considerably reduced to give a safe measure of the area which was operative at the time of the

inter-glacial epochs, or at least some of them, for there is abundant evidence that the land was not then so greatly elevated as in the Ozarkian or Sierrian period.

Instead, therefore, of combining 20 per cent. increase of land area with 100 per cent. increase of elevation, and these with the coöperating 20 per cent. reduction of sea area, the destruction of sea-shelves, and the restraining effects of lowering temperatures, as we are entitled to in bringing down the rich Tertiary atmosphere to the lean conditions of the glacial period, let us content ourselves with some modest fraction of these intensifying combinations. If we only assume that the agencies of depletion were superior to the agencies of return by the amount of 10 per cent., the depletion requisite to bring on a glacial epoch, starting with atmospheric conditions like those of the present, would be effected in less than 10,000 years. If, therefore, we over-generously allow as much time for deglaciation as for reglaciation, an interglacial epoch might not require the operation of the postulated agencies for more than 20,000 years, so far as they themselves are concerned. The development of the ice-sheet might take more time, but we have little or no data for estimating this. If 10,000 years additional is allowed for this the total remains at the modest figure of 30,000 years.

It would not seem to be pushing the data previously given to extremes to postulate a larger percentage of difference between depleting and repleting agencies than 10 per cent., which would make the requisite atmospheric depletion possible in a shorter period. It is probably not extravagant to assume that the difference might rise to 20 per cent., in which case the requisite time would be brought down to extremely modest limits. It is difficult to see how anyone who studiously considers the phenomena of the Toronto interglacial epoch could assign to it a duration less than is compatible with these agencies, as here interpreted. It would seem, therefore, that the hypothesis is not excluded from the working category by inadaptibility to the time rates of the phenomena which it seeks to elucidate.

There is not likely to be any serious question respecting the

time rates at the other extreme, that is, that the agencies necessarily act too rapidly to correspond to the phenomena. Of course, in the final adjudication of the hypothesis, it will be necessary to show that its time rates not only might correspond to the time rates of the phenomena, but that they did so, but this is a labor of the future, and is obviously dependent upon a very notable extension of precise knowledge, which it is the purpose of the hypothesis to aid in calling forth. It is sufficient here to show that reasonable postulates, based on a reasonable estimate of the phenomena, fall within compatible limits.

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(To be continued.)